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Booster RF Cavity Replacement

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PIP-II Collaboration Meeting

9-10 November 2015

Why?

- While the existing cavities have been refurbished, they are still 40 years old.
- PIP II operations will leave no extra operating margin.
- Uncertain operational impact of needing to run all cavities at maximum performance 24/7.

PIP & PIP-II high level performance goals

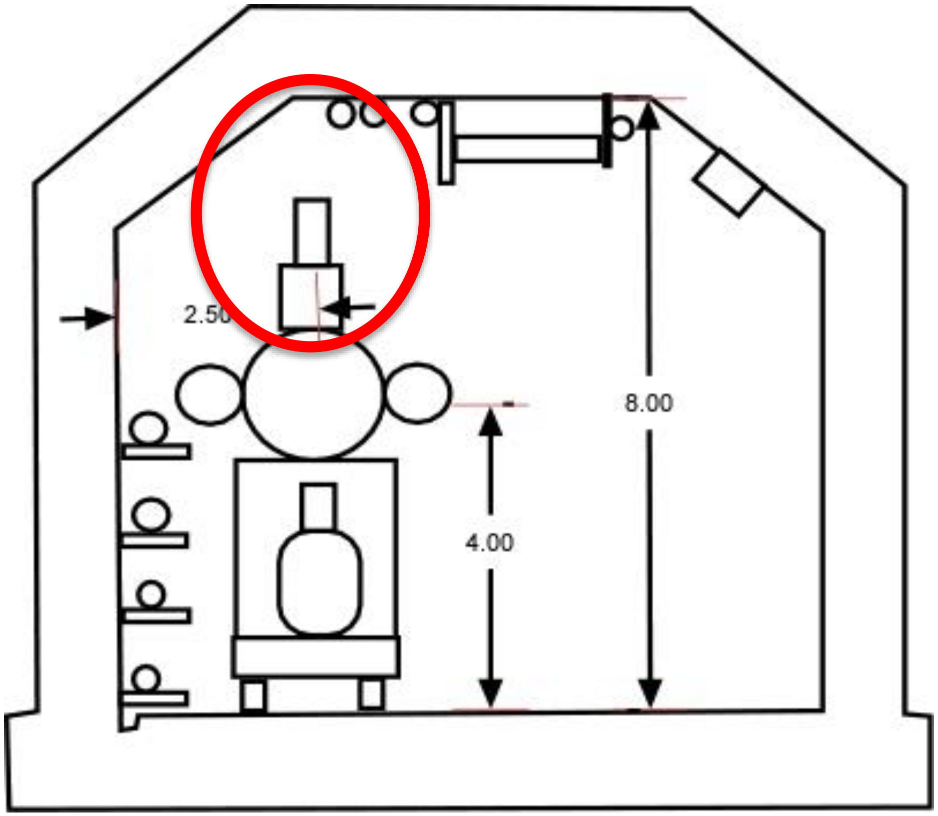
Beam Performance Parameter	PIP	PIP-II	
Injection Energy	400	800	MeV
Linac Particle Type	H^-	H^-	
Linac Beam Current	27	2	mA
Linac Beam Pulse Length	0.03	0.5	msec
Beam Capture	Adiabatic Paraphase	Bucket to Bucket	
Booster Pulse Repetition Rate	15	20	Hz
Booster Protons per Pulse	4.2×10^{12}	6.4×10^{12}	
Booster Beam Power @ 8 GeV	80	160	kW
Beam Emittance (6s, normalized; ex=ey)	<18	<18	π mm-mrad
Delivered Momentum Spread (97% full height)	12.2 Momentum Spread (97% full	12.2 Momentum Spread (97% full	MeV Momentum Spread (97% full
Delivered Longitudinal Emittance (97%)	.08	.08	eV-sec

PIP & PIP-II RF Parameters

Cavity Performance Parameter	PIP	PIP-II	
Frequency Sweep	37 to 53	44.7 to 53	MHz
Cavity Tuning (Bias Supply Max Current)	3000	3000	amps
Modulator Voltage (Max: Anode – drop)	30	30	kV
Higher Order Mode	< 1000	<1000	Ohms
Aperture	~ 3	~3	inch
*Total Voltage	1000	1100	kV
Overhead Voltage	100	100	kV
Duty Cycle	50	50	%
Cavity Q	300 to 1250		
Shunt Impedance	17 to 61.25		k Ohms
LCW Cooling Temp (actual)	95 (88 – 94)	95 (88 - 94)	F
LCW Flow	100	100	PSI
Forced Air Cooling	Yes	Yes	

* Sum of gap voltages at peak power, overhead allows for running with reduced # of cavities.

Tunnel Constraints



Must fit in existing tunnel, limitation of options for new Pas.

Cavity Voltage

- Present
  - 830 kV – 950 kV, present operating range depending upon beam requirements and cavity repair status.
  - < 850 kV, losses increase for 4.2E12/pulse.
    - requires a minimum of 17cavities at the nominal voltage 50 kV or 25 kV/gap.
- PIP II requirement
  - 1.2 MV (1.1 MV total + 0.1 MV overhead)

	Voltage per Cavity			
# of cavities	Present 870 kV	Soon 950 kV	Next Year 1005 kV*	Replacement 1200 kV
19	45.8 kV			
20		47.5 kV		60 kV
21			47.8 kV	57 kV
22			45.7 kV	55 kV

* If funding allows

- Plan to run similar to MI, all cavities on, voltage fixed/regulated as needed.

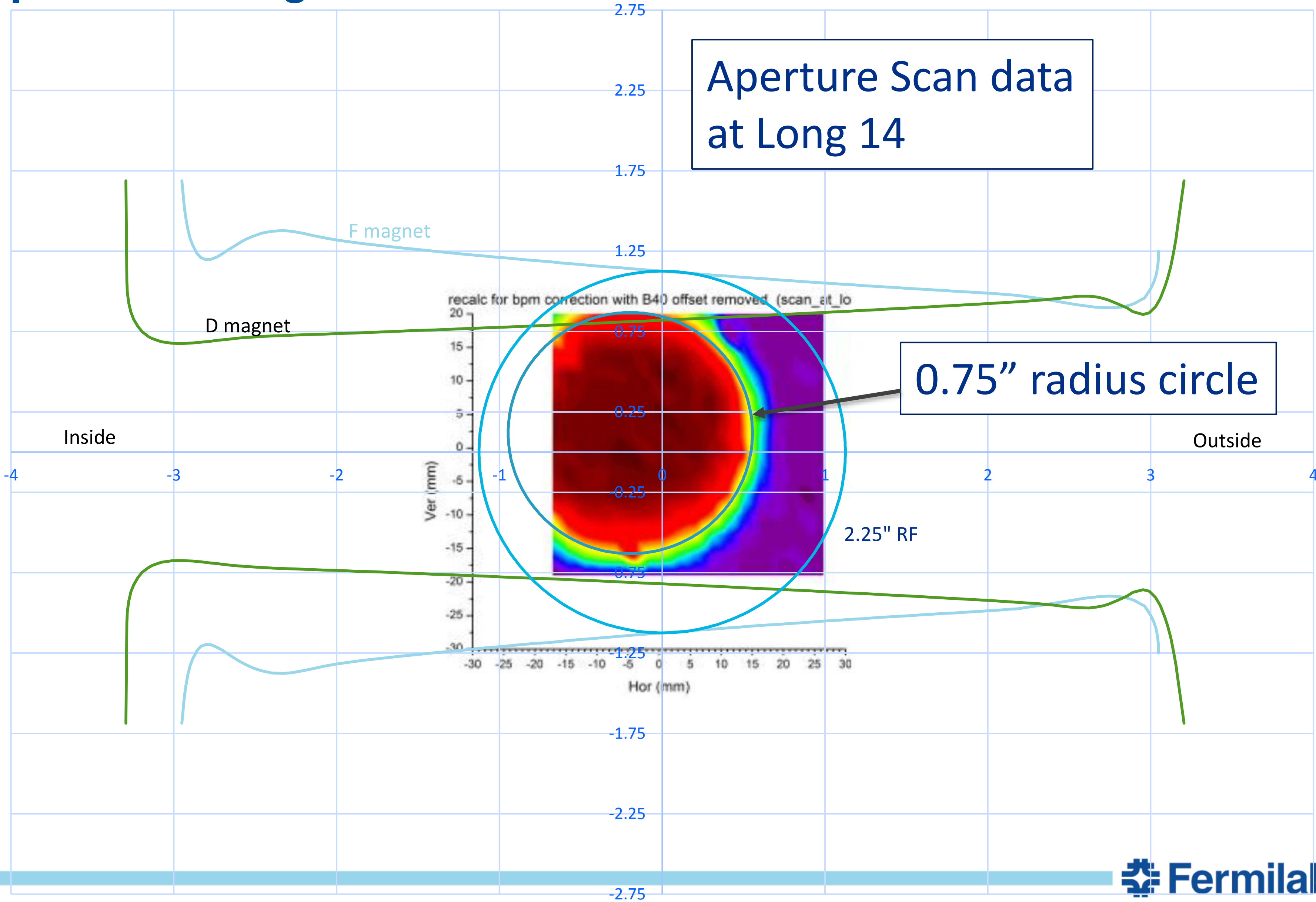
Cavity Tuning and Drive System

- Will use existing hardware which was all recently upgraded for PIP
  - New solid state driver system
  - Upgraded bias supplies
  - New anodes – higher power
  - Additional cooling (air & LCW) systems for RF systems
  - Upgrades on low level controls
- This task of the PIP project is replacement of cavities only

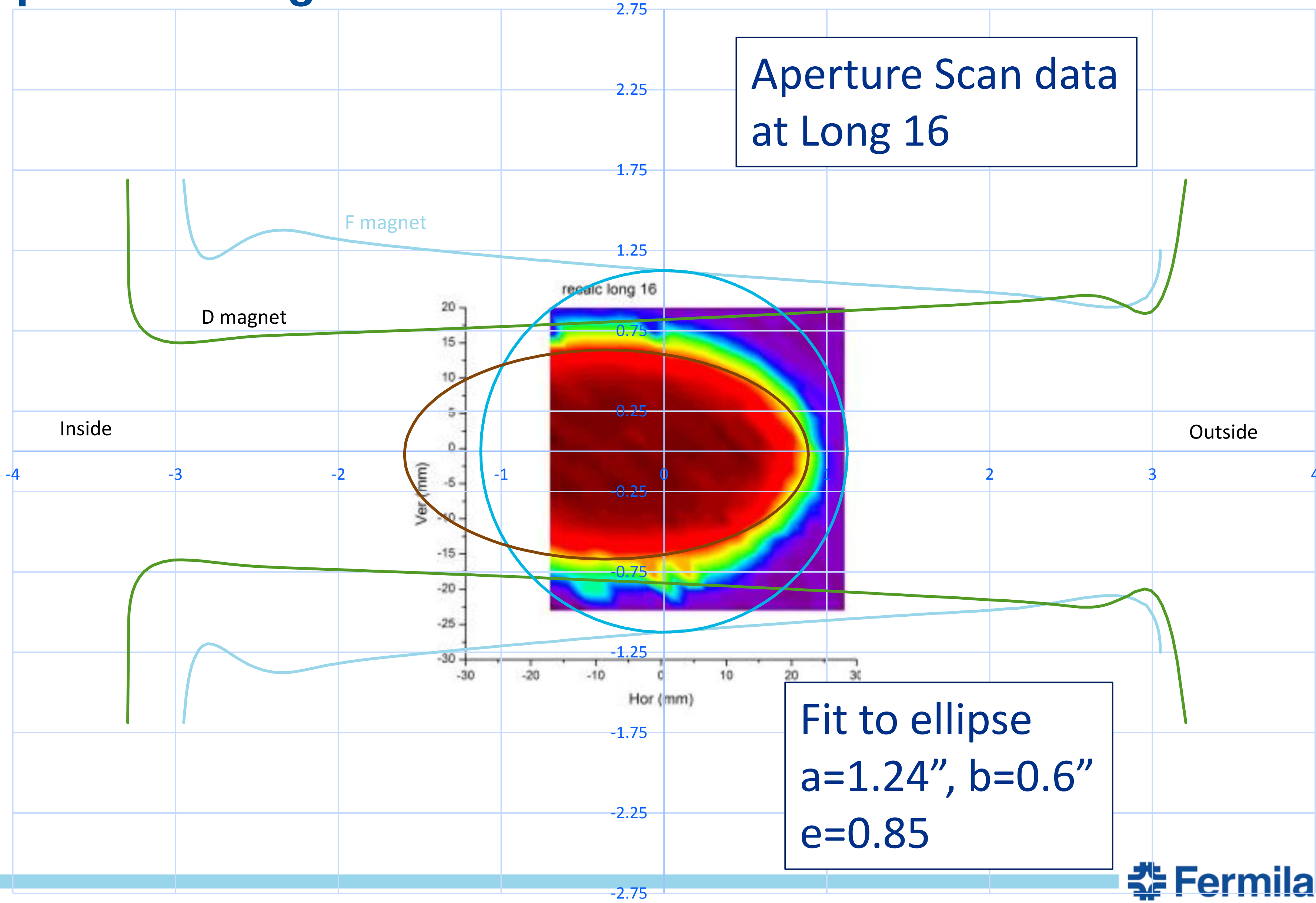
Other cavity performance factors

- **Beam Loading and Power Requirements**
  - Each cavity must meet the specified voltage while accelerating up to 1000ma of beam (at a synchronous phase of ~40 degrees (synchrotron definition, 90 degrees at crest)) with 2-3 of the 84 buckets empty.
  - The loaded cavity shall be designed to operate with up to 150 kW RF power from a CPI (EIMAC) Y-567B tetrode power tube. Although rated to operate at higher power up to 200 kW, for lifetime considerations operating at a lower power is preferable.
- **Cavity Impedance and Spurious Modes**
  - The cavity shall be designed for R/Q = 50 ohms and the impedance of all higher order and spurious modes shall be ≤ 1000 ohms.
- **Multipacting**
  - The cavity must be able to turn on and run at any voltage between 25% and 100% of the specified operating voltage over the full frequency range without operationally significant multipacting at the nominal operating vacuum pressure.

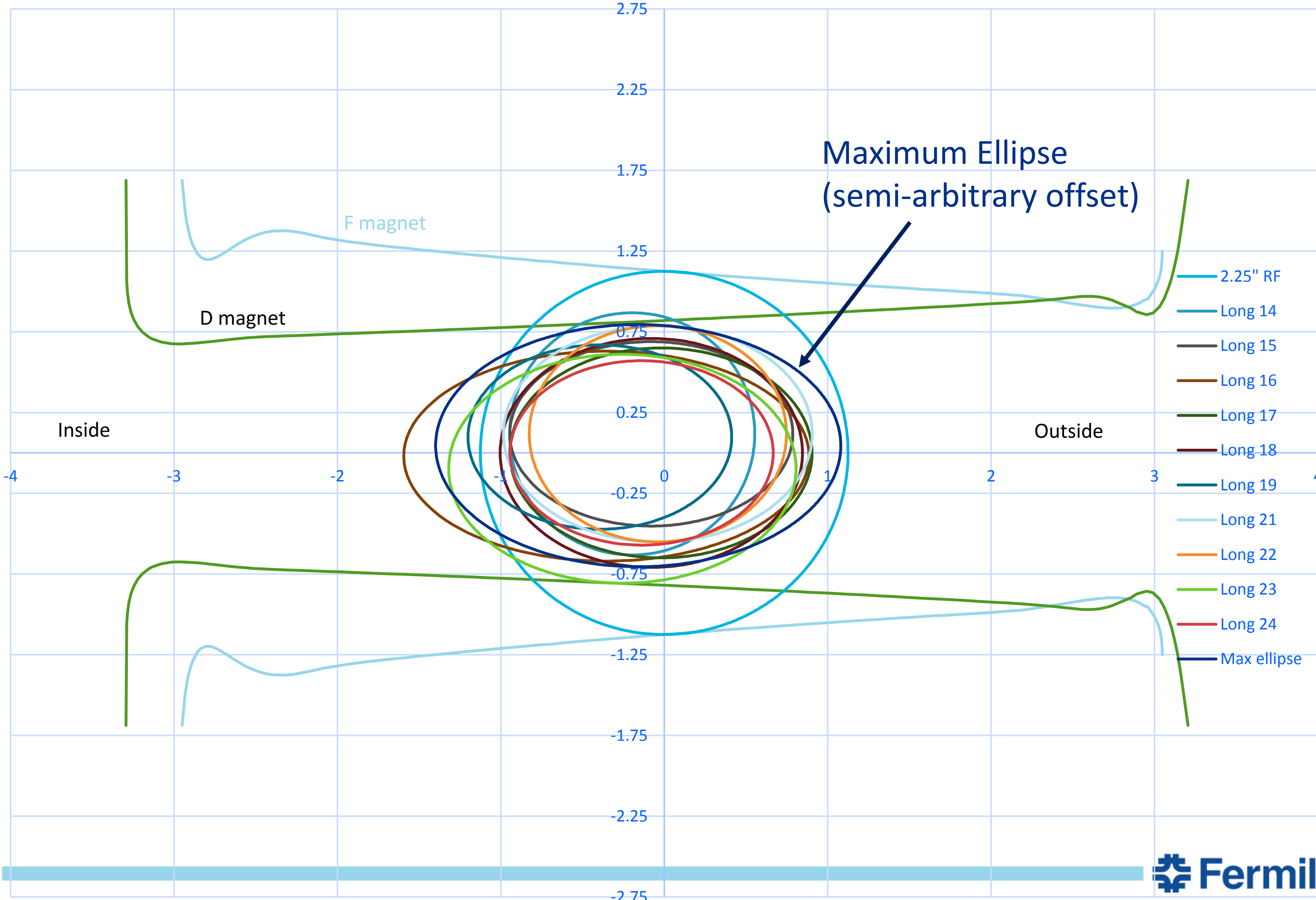
Aperture - Magnets and RF



Aperture - Magnets and RF



Aperture - Ellipse using maximum parameters



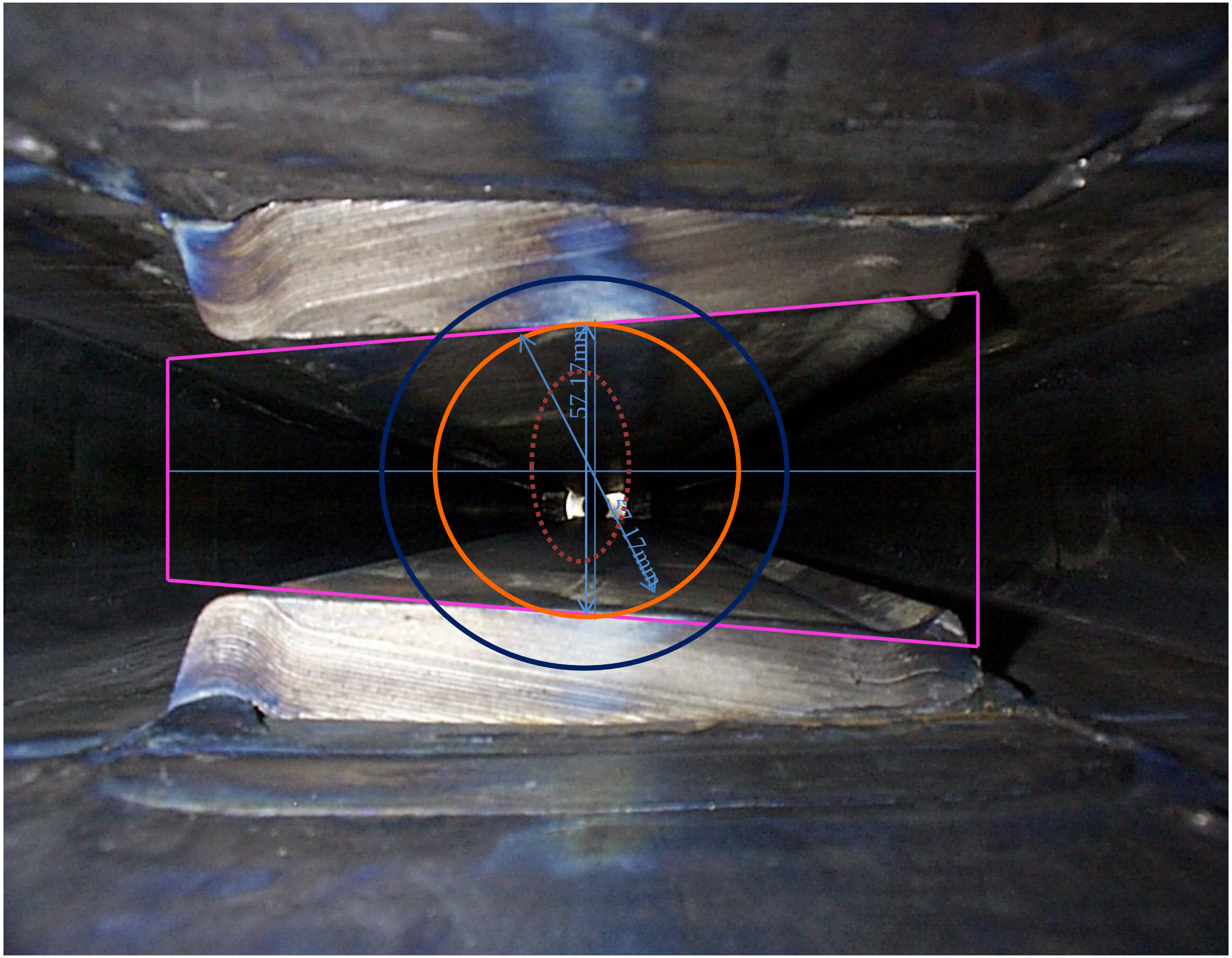
Aperture - Conclusion

	a (inch)	b (inch)	area (in^2)
average	0.9113	0.6519	1.87
max	1.24	0.75	2.92
Ratio (max/ave)	1.36	1.15	1.57
New aperture radius	1.53	1.29	6.22

Radius = 1.4

3” beam pipe will provide 0.1” to 0.2” margin

Aperture – Second Look



- Vertical aperture limited by magnets
- Horizontal aperture limited by cavities

PIP-III Beam Parameters

Table 3	**Booster (PIP)**	**PIP II**	**New RCS (PIP III)**
Pulse Intensity	4.3E12	6.5E12	30E12
Peak RF Beam Current	.86 amps	1.3 amps	6 amps
Cycle Rep Rate	15	20	20
Injection energy	.4 GeV	.8 GeV	2 GeV*
Extraction energy	8 GeV	8 GeV	8 GeV
Revolution time	2.22 to 1.59 us	1.88 to 1.59 us	1.66 to 1.59 us

*Representative value (still under discussion)

PIP-III Cavity Parameters

Table 4	**Booster (PIP)**	**PIP II**	**New RCS (PIP III)***
Frequency Sweep	37 to 53 MHz	44 to 53 MHz	50 to 53 MHz
Peak DP/DT MeV/.1ms	376	470	387
Peak eV/turn	606	755	620
Harmonic #	84	84	84

* No design available – basic assumptions about beam current and injection energy

Review

- Consensus
  - New cavities – yes
  - Larger bore necessary for PIP-III suggested but impact on design not understood
  - Continue simulation efforts for II & ⊥ bias cavities
  - Prototypes for II & ⊥ bias cavities
- Questions
  - Wait for results of ⊥ bias ?
  - Cost trade-off between copper and garnet
- Additionally
  - Instrumentation, feedback, and control needs to be upgraded for reliable operation at projected beam powers

Conclusion

- No upstairs systems are involved
  - All necessary upgrades will have been completed as part of PIP
- Physical constraints remain the same – no tunnel modifications anticipated
- Beam parameters for PIP-II are set
- Cavity specs are complete and can be applied to either:
  - Parallel bias cavity or
  - Perpendicular bias cavity
- Major cavity specs are compatible with PIP-III/RCS
  - Detailed specs will determine whether cavities can be used
- Work ramping up in FY16 with plans to test prototype in FY17

Fermilab

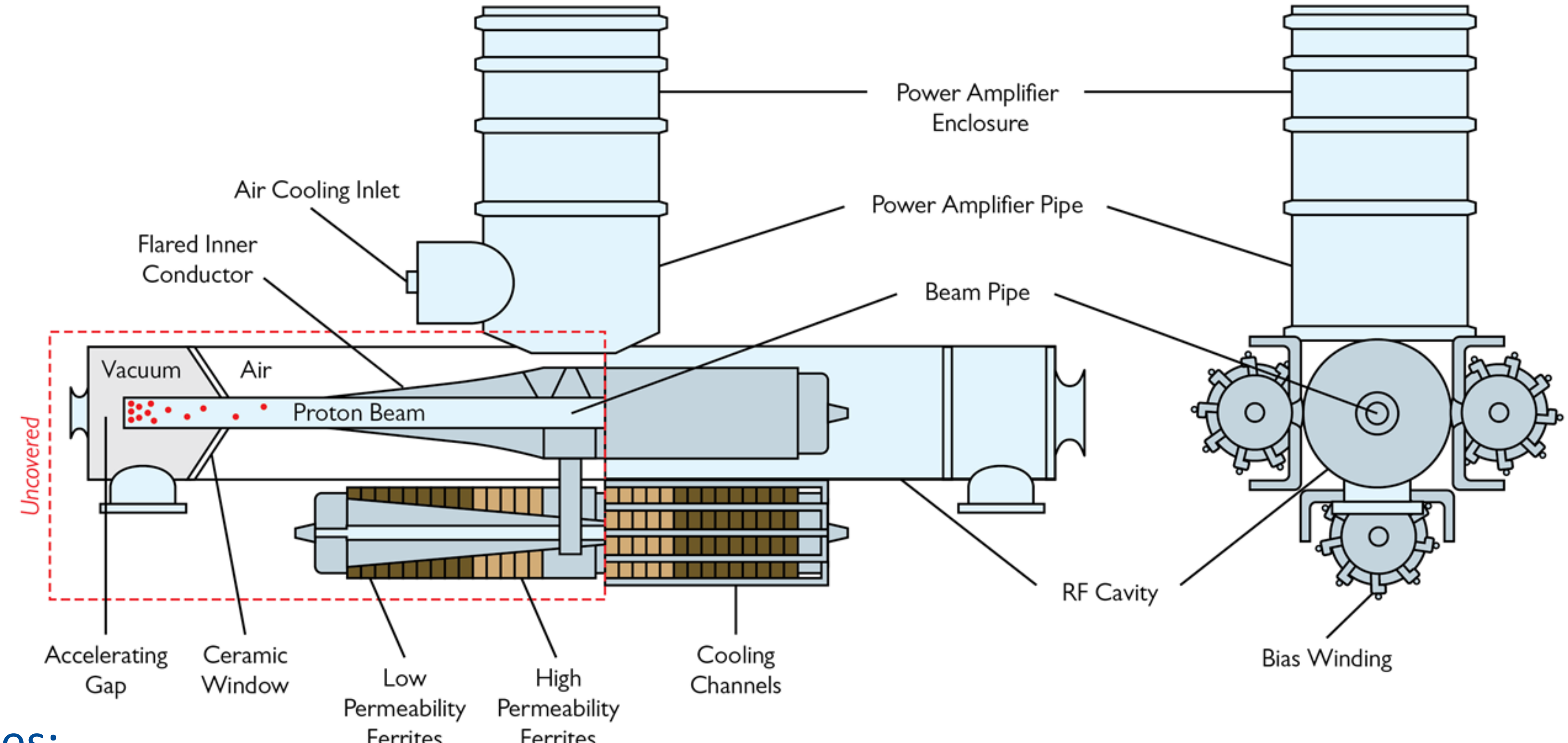
Electromagnetic Modeling of Fermilab's Booster Cavity

Mohamed Hassan

Workshop on Booster Performance and Enhancements

24th Nov 2015

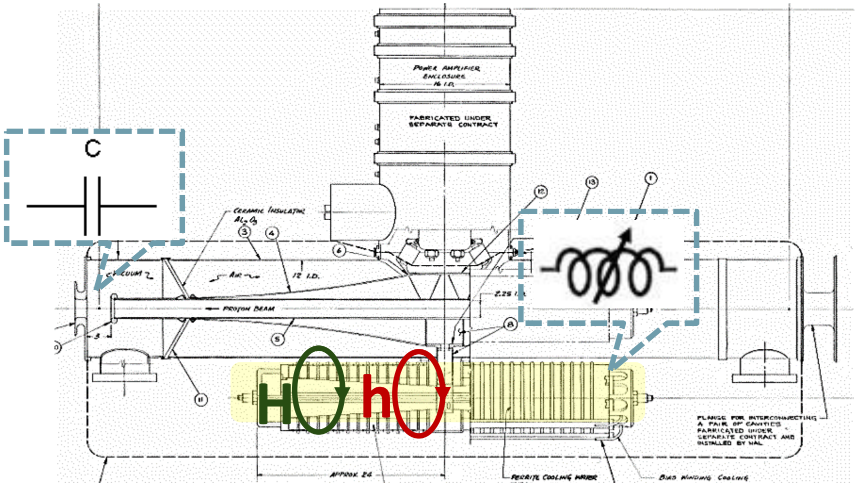
Geometry of Fermilab’s Booster Cavity

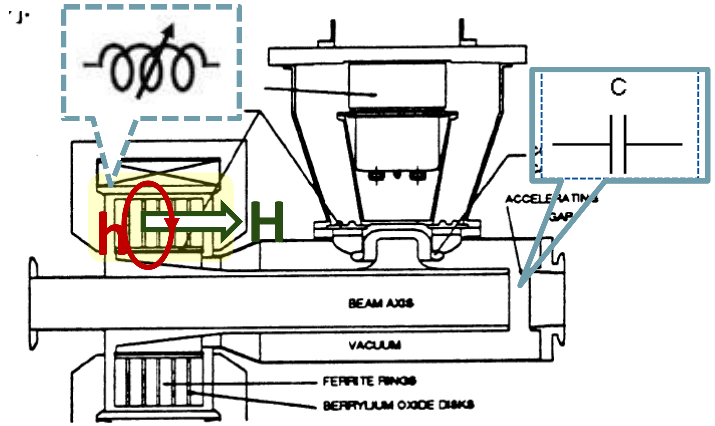


Issues:

- RF heating with increased duty cycle (resolved for 15 Hz by additional air/water cooling)
- Activation of beam pipe (need for larger bore)
- Occasional voltage breakdown (need for better tuner connection)

Tunable Booster Cavities





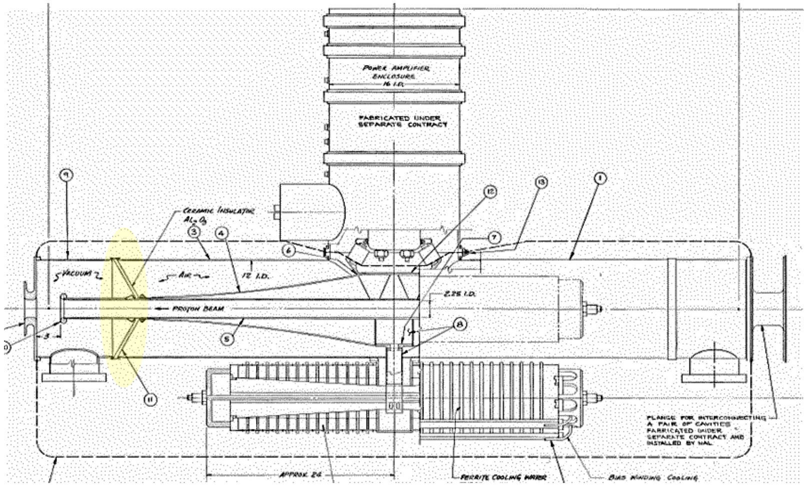
Parallel Biased	Perpendicular Biased
Bias Field is Parallel to the RF Field	Bias Field is Perpendicular to the RF Field
$H\widehat{\varphi} + h\widehat{\varphi} = (H+h)\widehat{\varphi}$	$H\hat{z} + h\widehat{\varphi} =$ rotating (on cone) magnetic vector – Gyromagnetic Resonance H=f/2.8
Ferrites with High Saturation Magnetization (Ni-Zn)	Ferrites with Relatively Low Saturation Magnetization (Mn-Zn)
Larger values of Mu (Larger Losses, Lower Q)	Smaller values of Mu (Smaller Losses, Larger Q)

Comparison Between Existing Relevant Booster Cavities

	FNAL Booster	TRIUMF	SSCL LEB	EHF-Booster
Energy Range [GeV]	0.4-8.0	0.45-3.0	0.6-11	1.2-9.0
Bias	Parallel	Perpendicular	Perpendicular	
Frequency [MHz]	37.7-53.3	46.1-60.8	47.5-59.8	50.5-56.0
Peak Gap Voltage [kV]	2*27	62.5	127.5	2*36
Cavity Length [m]	~2.4	~1.23	~1.25	~3.25
Accelerating Time [ms]	35	10	50	20
Repetition Rate	7	50	10	25
Ferrite Material	Ni-Zn	Yttrium Garnet	Yttrium Garnet	
Ferrite Material	Toshiba, Stackpole	TT-G810	TT-G810	
Cavity Q	250-1200	2200-3600	2800-3420	
Cavity R/Q	50	35	36	
Status	**Operating**	**Prototype**	**Prototype**	

Development of perpendicular-biased cavities didn't pass prototype stage

Why Perpendicular Biased Cavity Could Achieve Higher Voltage Gradient?



- Air fills most of the cavity volume (breakdown ~30 kV/cm)
- Vacuum windows are nearby the gap
- Tuner is filled with air

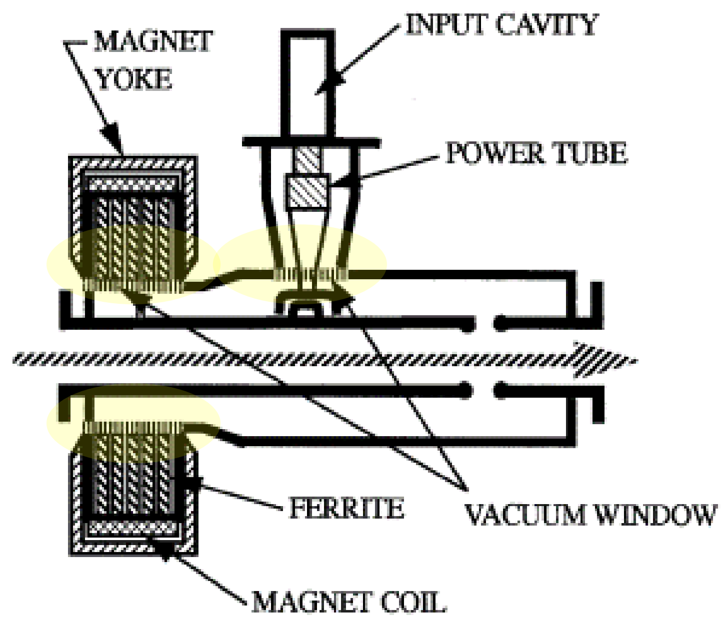
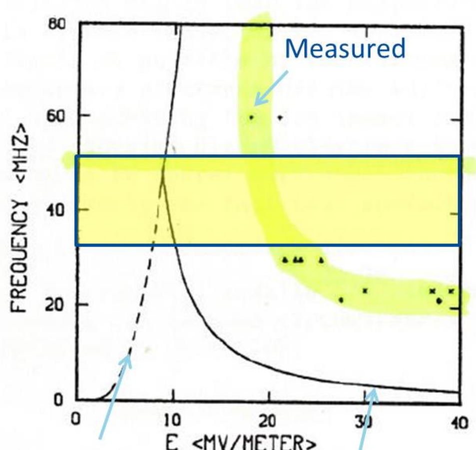


Figure 1. LEB prototype cavity.

- Vacuum fills most of the cavity volume (breakdown ~ 100 kV/cm)
- Vacuum windows are right away on the tuner connection
- Tuner is filled with dielectric



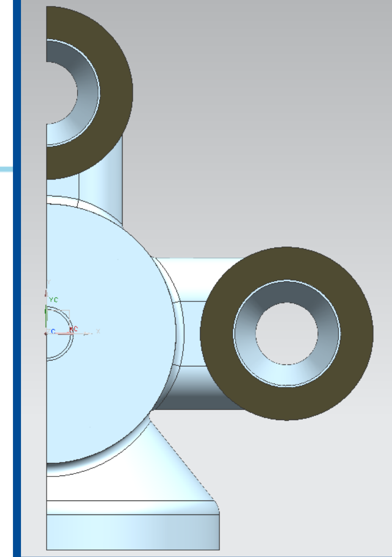
Theoretical Kilpatrick

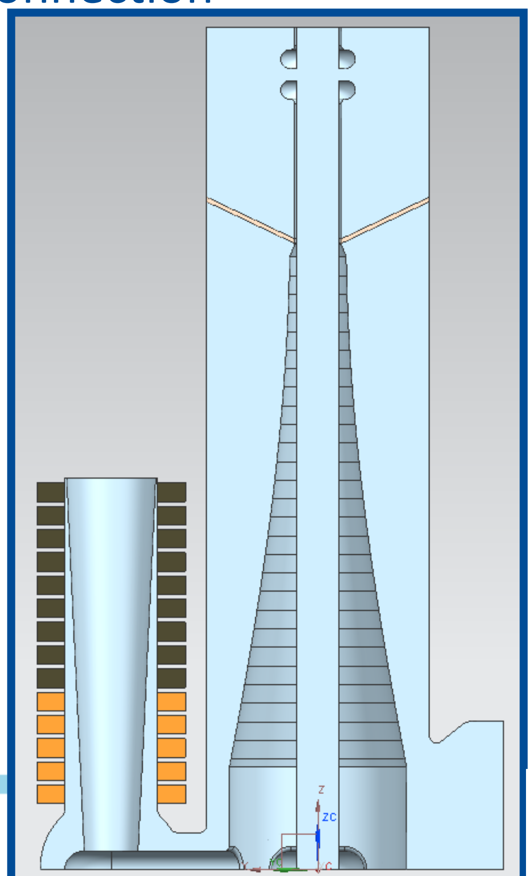
Theoretical Peter et. Al.

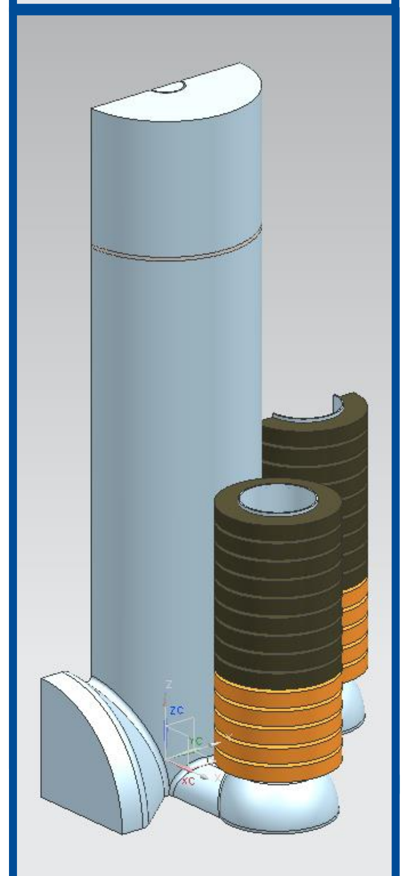
In Air ~ 3 MV/m (30 kV/cm)
In Vacuum (according to Kilpatrick) is ~ 10 MV/m (theoretical) 18 MV/m (measured)

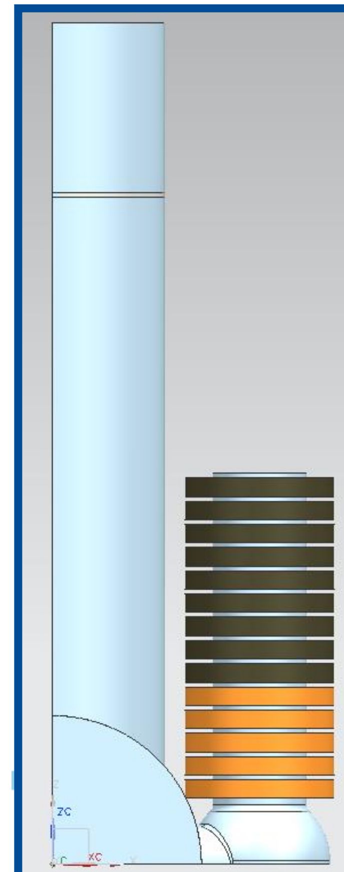
Full 3D Model

- Realistic Tuner with all the fine details
    - 5 Toshiba Ferrites
    - 9 Stackpole Ferrites
    - Flared Inner Conductor
- Realistic Tuner Connection







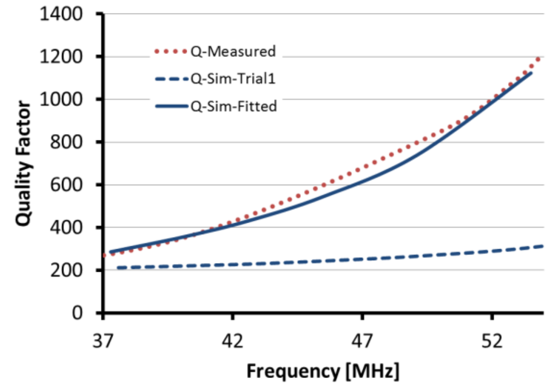


Possible Changes to the Current Design

- Rounding the stem corners with large radius >0.25” to reduce the risk of voltage breakdown in air-filled regions
- Enlarging the stem connection between the tuner and the cavity would help to reduce tuner losses
- Improve the connection of the vacuum window and cavity to reduce ceramic window failures
- Can we fill the tuner with another medium other than air?

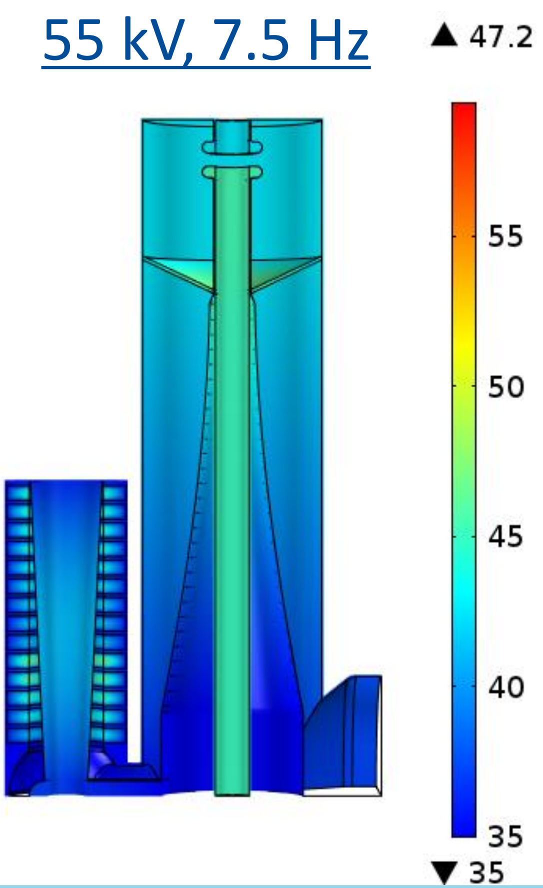
Regular Cycle 7.5Hz vs 15Hz

- Simulated Q has been fitted to the measured one by adjusting the magnetic loss tangent with frequency

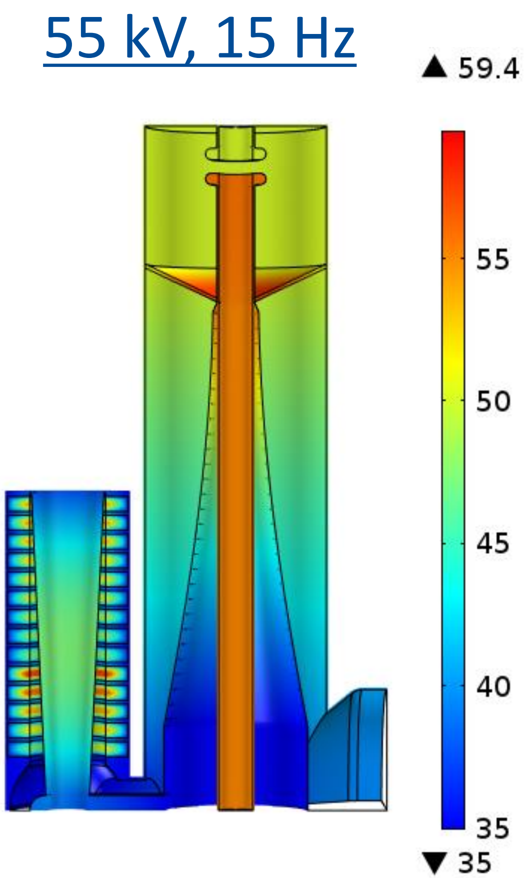


Max T=47.2° C

Constant Temp Boundaries



Constant Temp Boundaries



CW Simulation vs Measurements Results

Measurements data were collected for various CW fixed frequency cases (22kV)

Simulations	50 MHz	45 MHz	40 MHz
Frequency [MHz]	**49.998**	**45.0163**	**39.979**
Unloaded Quality Factor	**773**	**513**	**348**
Gap Volatge [kV]	22.00	22.00	22.00
Volume Losses [kW]	5.01	9.25	16.88
Surface Losses [kW]	1.03	1.09	1.18
Total RF Losses [kW]	**6.04**	**10.34**	**18.07**

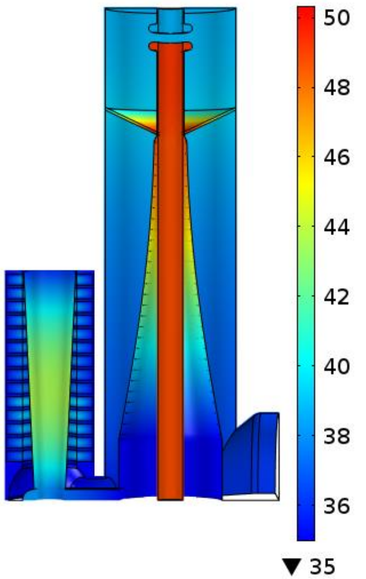
	50 MHz	**45 MHz**	**40 MHz**
Total RF Losses [kW]	6.04	10.34	18.07
P_RF_Water [kW]	5.48	8.58	13.79
Descrepancy %	**10.34**	**20.56**	**31.02**

Measurements	50 MHz	45 MHz	40 MHz
Bias Current [A]	1290	640	325
Bias Voltage [V]	5.296	2.544	1.286
Pbias [kW]	6.83	1.63	0.42
Anode Volatge [kV]	10	10	10
Plate Current [A]	2.2	2.4	3.06
Input RF Power [kW]	22	24	30.6
Frequency [MHz]	**49.898**	**44.878**	**40.056**
Unloaded Quality Factor	**678**	**435**	**330**
Gap Volatge [kV]	22	22	22
f_water [Hz]	200.2	200	197.7
K-Factor	938	938	938
Water Flow [gpm]	12.81	12.79	12.65
dT_bias	1.95	0.45	0.12
P_bias [kW]	6.59	1.52	0.40
dT_withAir	3.28	2.70	4.19
dT_noAir	3.57	2.99	4.25
P_air [kW]	0.98	0.98	0.20
P_Water [kW]	12.07	10.10	14.19
P_RF [kW]	**5.48**	**8.58**	**13.79**

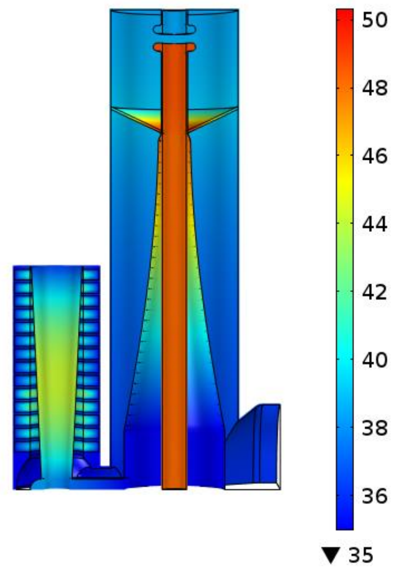
Measurement data provided by **John Reid**

Simulation vs Measurements

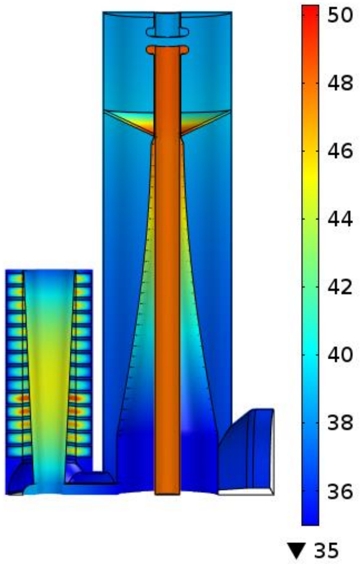
50 MHz, 22 kV, CW



45 MHz, 22 kV, CW



40 MHz, 22 kV, CW



50 MHz	Tfront [C] (FR99T)	Tback [C] (BA99T)	Tcavity [C] (BA99RT)	Tbottom [C] (AD99DT)
Base	34.02	33.49	32.49	32.72
Air is ON Steady State	40.55	38.07	36.52	36.74
Air is OFF Steady State	**49.18**	**46.11**	**47.44**	**41.01**

45 MHz	Tfront [C] (FR99T)	Tback [C] (BA99T)	Tcavity [C] (BA99RT)	Tbottom [C] (AD99DT)
Base	32.47	31.97	30.31	32.15
Air is ON Steady State	38.44	36.33	34.88	35.41
Air is OFF Steady State	**45.96**	**43.32**	**44.57**	**39.25**

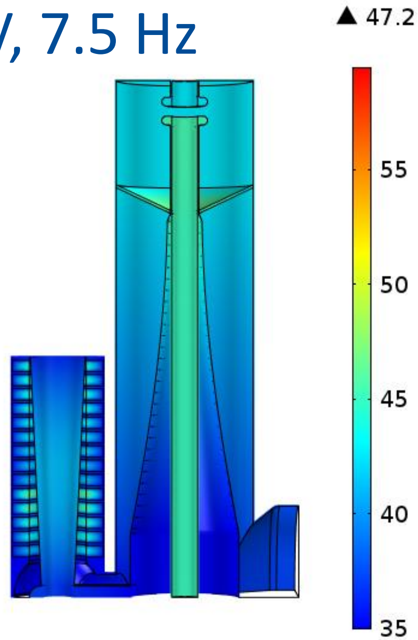
40 MHz	Tfront [C] (FR99T)	Tback [C] (BA99T)	Tcavity [C] (BA99RT)	Tbottom [C] (AD99DT)
Base	31.66	31.15	29.61	31.27
Air is ON Steady State	38.00	36.00	34.00	35.00
Air is OFF Steady State	**43.57**	**41.36**	**42.3**	**38.28**

	Parallel Biased		**Perpendicular Biased	
Length [m]	2.3		1.1	
Height [m]	0.56		0.5	
Aperture [in]	2.25		3.25	
Volume of Ferrites [m^3]	0.04216		0.03626	
Cost				
Gap Voltage [kV]	55		55	
Frequency Sweep [MHz]	37.3	53.8	37.2	53.8
Permittivity	12.0*(1-j*0.005) 10.5*(1-j*0.005)		14.0*(1-j*0.00015)	
Permeability	8.40*(1-j*0.0051) 5.25*(1-j*0.0037)	3.00*(1-j0.0018) 1.88*(1-j*0.0013)	4*(1-j*0.003)	1.5*(1-j*0.00036)
Q	285	1102	385	4004
Energy [mJ] CW	171.59	59.40	95.79	68.35
Volume Losses CW	141.27	18.23	57.96	5.58
Surface Losses CW	6.98	5.92	0.36	0.72
Total Losses CW	148.25	24.15	17.1	3.0
E_{max} in Air [MV/m]	1.67	0.91	-	-
E_{max} in Vacuum [MV/m]	2.2	2.2	4.6	4.6
E_{max} in Ferrite [MV/m]	0.21	0.10	0.32	0.21
T_{max} [C] at 7Hz/15Hz	47.2/59.4		77.2/119.0	
Energy [mJ] at 7Hz/15Hz	0.25/0.5*66.86		0.25/0.5*47.51	
Total Power Loss [kW] at 7Hz/15Hz	14.4/28.9		7.23/14.5	

*Cycle Energy is assumed to be 0.579*Avg Energy **Cavity geometry is based on TRIUMF with no further optimization

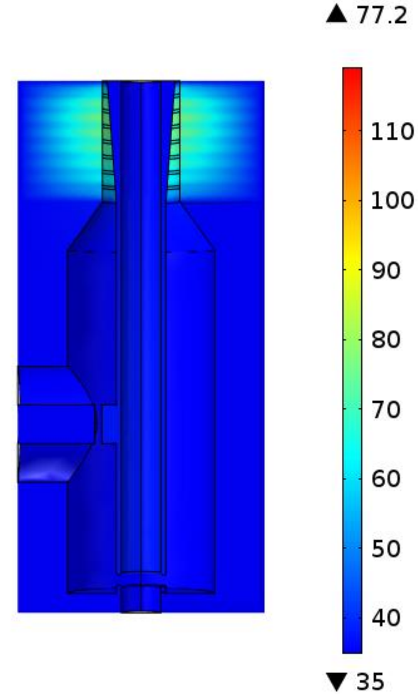
55 kV, 7.5 Hz

Constant Tem Boundaries



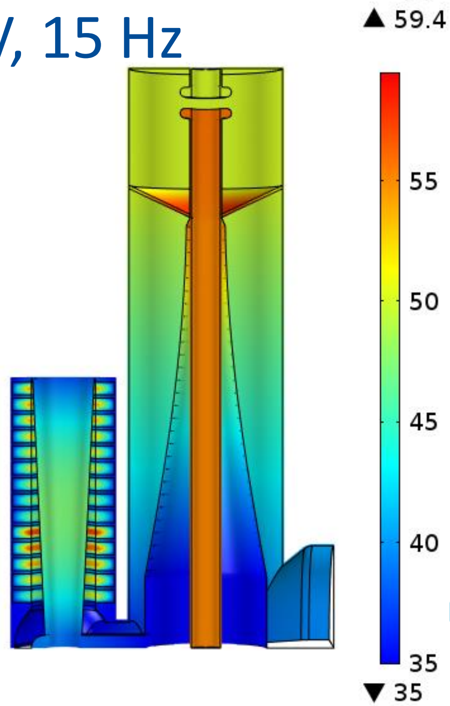
55 kV, 7.5 Hz

Constant Temp Boundaries



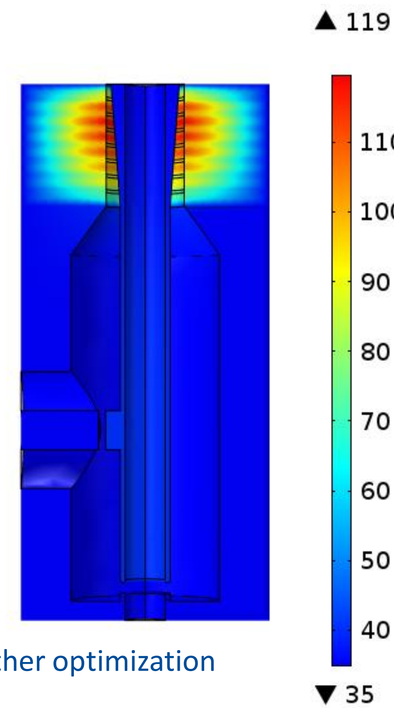
55 kV, 15 Hz

Constant Ten Boundaries



55 kV, 15 Hz

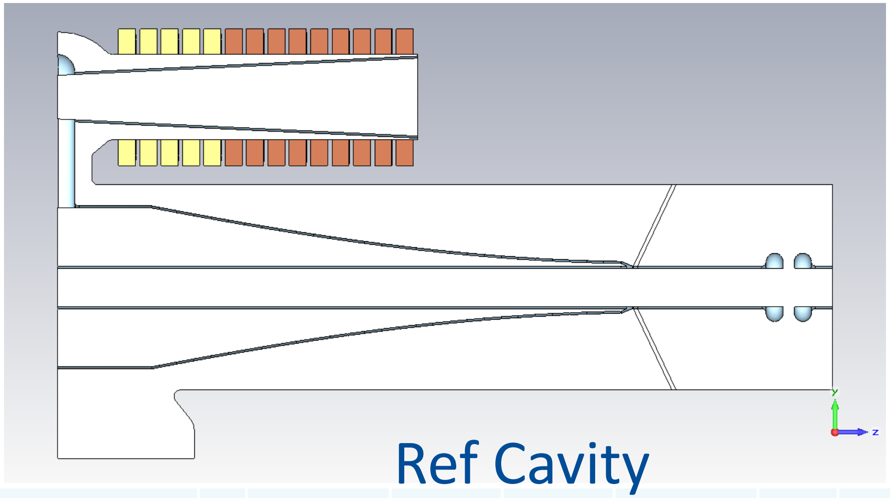
Constant Temp Boundaries



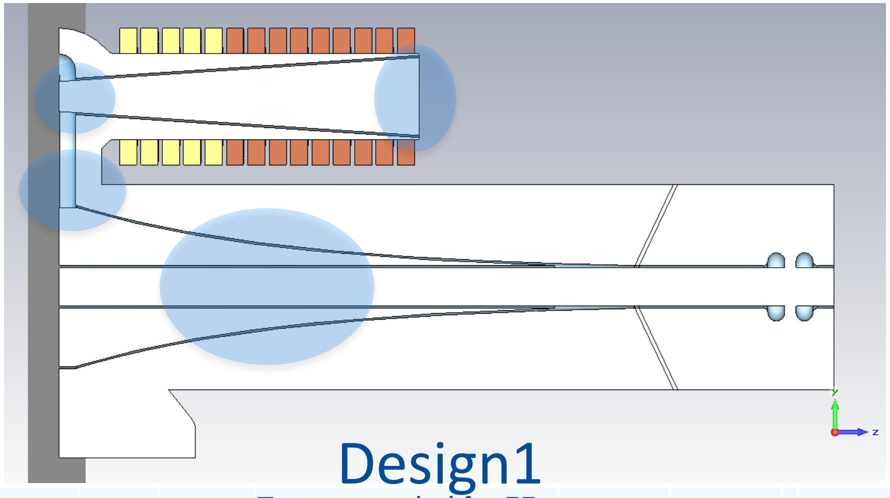
*Cavity geometry is based on TRIUMF with no further optimization

Preliminary New Design

- Carried out full parametric study
- Identified changes that can help lower the losses in the cavity



Ref Cavity

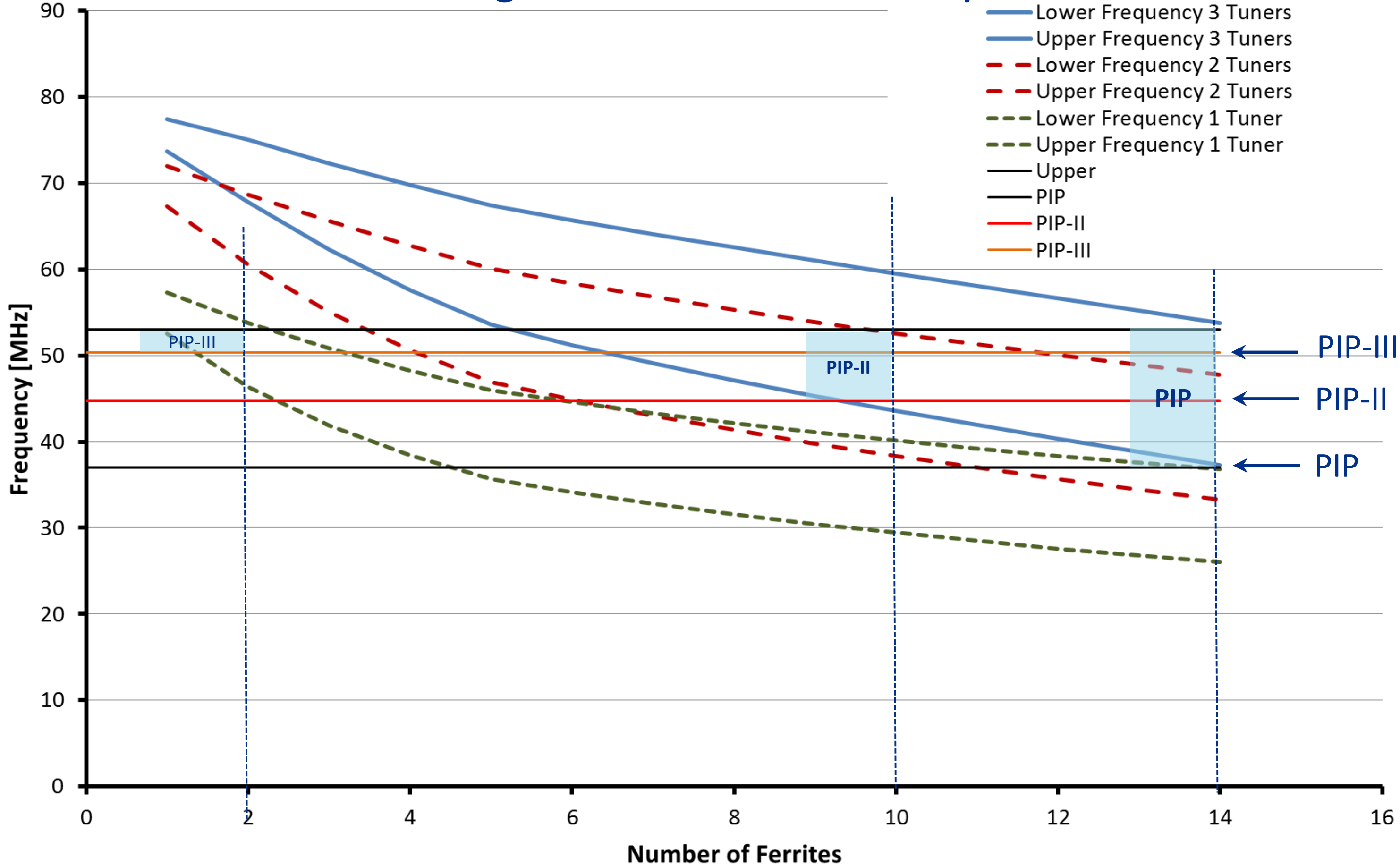


Design1

	fa1 [MHz]	f1 [MHz]	f2 [MHz]	fa2 [MHz]	Qa1	Q1	Q2	Qa2	Ea1[mJ]	E1 [mJ]	E2 [mJ]	Ea2[mJ]	Eav [mJ]	Eint [mJ]	BW[MHz]
		mu=8.4	mu=3							Energy needed for 55 kV					
Ref Cavity	**37.3**	**37.3**	**53.5**	**53.5**	**286**	**286**	**1123**	**1123**	**42.9**	**42.9**	**14.8**	**14.8**	**28.85**	**19.9065**	**16.2**
	mu=11	mu=8.4	mu=3	mu=3.5											
Design1: Rconn=2.5, Rtunner1=1 , Ls=1, Rpipe=1.125, C=-0.08	37.5	41.5	55.3	53.6	229	322	1616	1230	28.6	21.3	8.4	9.4	19	13.11	13.8

- Sacrifice for 2.4 MHz in bandwidth that will need to be compensated for by biasing less the ferrites
- About 30% saving in power loss

Mu of ferrites changes to mimic the bias cycle



	PIP [37-53 MHz]	PIP-II [44.7-53 MHz]	PIP-III [50.3-53 MHz]
3-Tuner Design [37-53 MHz]	✓	✓	✓
2-Tuner 10F/H [43.6- 53 MHz]		✓	✓
1-Tuner 2F/H [46.4-53.7 MHz]			✓

Conclusion

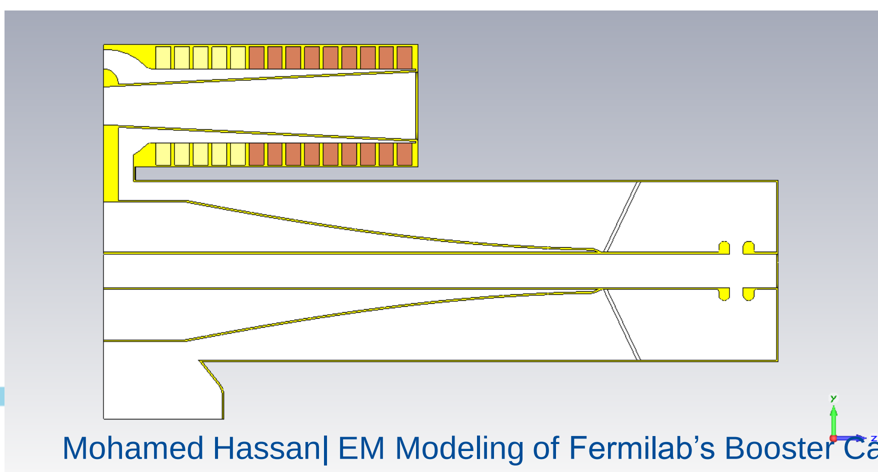
- A full detailed 3D model to the current cavity has been built
- Current cavity has been subject to extensive electromagnetic and thermal analysis
- We were able to compare simulation and measurements for CW operations with fairly good agreement
- Further measurements are planned
- We carried out a full parametric study to the current cavity geometry
- Modifications to the current cavity have been proposed
- We have also explored the possibility of operating the cavity under PIP-II and PIP-III frequency sweep scenarios

Fermilab's Booster Cavity

Criteria of Comparison?

- With eigen-mode simulation, the quality factor and energy (not the power) that would produce a required gap voltage could be calculated
- Decreasing the energy needed for 55 kV gap voltage (increasing the Q) simply means less power loss inside the cavity thus less heating
- These performance indicators will be calculated at two permeability values, namely; 8.4 and 3.0 that corresponds to the edge frequencies of the current booster operation

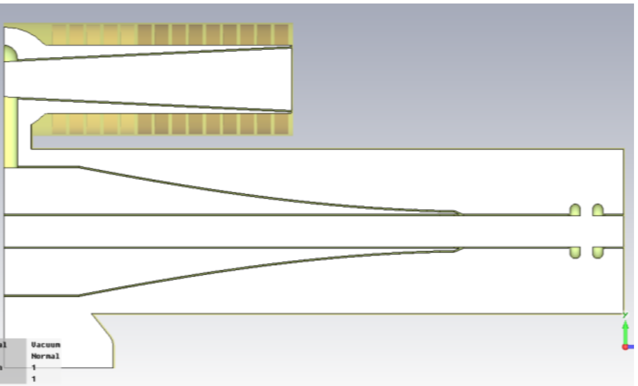
		mu=8.4	mu=3			Energy needed for 55 kV					
		f1 [MHz]	f2 [MHz]	Q1	Q2	E1 [mJ]	E2 [mJ]	Eav [mJ]	Eint [mJ]		BW[MHz]
Ref Cavity		37.3	53.5	286	1123	42.9	14.8	28.85	19.9065		16.2

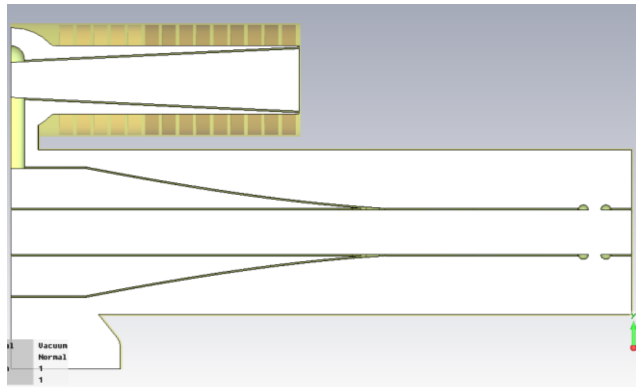


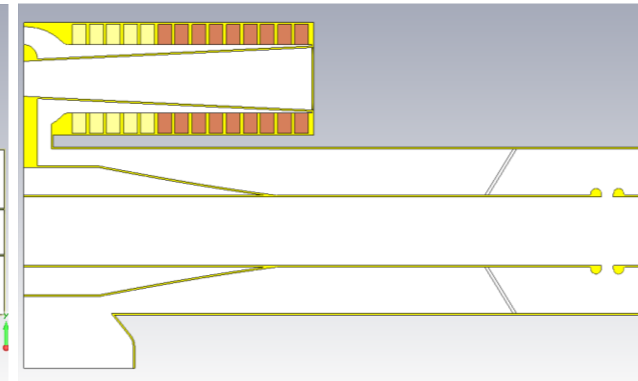
Simple Average

~Integral Average

Bore Radius Effect on the Cavity Performance







Rpipe=1.125 Rpipe=1.625 Rpipe=2.5

		mu=8.4	mu=3			Energy needed for 55 kV					
Rpipe		f1 [MHz]	f2 [MHz]	Q1	Q2	E1 [mJ]	E2 [mJ]	Eav [mJ]	Eint [mJ]		BW[MHz]
1		37.4	53.9	285	1100	43.6	15.2	29.4	20.286		16.5
1.125		**37.3**	**53.5**	**286**	**1123**	**42.9**	**14.8**	**28.85**	**19.9065**		**16.2**
1.625		37.1	53.2	287	1121	44.9	16	30.45	21.0105		16.1
2.5		35.3	49.4	297	1254	51.4	19.4	35.4	24.426		14.1

- Increasing the beam pipe radius has a considerable effect on both the bandwidth and Q factor